MODULARITY IN ROBOTIC SYSTEMS

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INTRODUCTION

Most robotic systems today are designed one at a time, at a high cost of time and money. This wasteful approach has been necessary because the industry has not established a foundation for the continued evolution of intelligent machines. The next generation of robots will have to be generic, versatile machines capable of absorbing new technology rapidly and economically. This approach is demonstrated in the success of the personal computer, which can be upgraded or expanded with new software and hardware at virtually every level.

Modularity is perceived as a major opportunity to reduce the 6 to 7 year design cycle time now required for new robotic manipulators, greatly increasing the breadth and speed of diffusion of robotic systems in manufacturing. This paper focuses on modularity and its crucial role in the next generation of intelligent machines. It begins by examining the main advantages that modularity provides; the second part of the paper discusses the types of modules needed to create a generic robot. The final section examines some structural modules designed by the robotics group at the University of Texas at Austin to demonstrate the advantages of modular design.

THE ADVANTAGES OF MODULARITY IN ROBOTICS

Modularity can be approached in almost all components involved in machine design - computer software and hardware, sensors, actuators, man-machine interface, etc. The advantages of modularity are readily illustrated by examining its impact in the areas of portability, precision, reliability, and economics.

PORTABILITY

Portability of a robotic system implies that it can be broken down into pieces (or modules) small enough to be carried to the work place by a human operator and quickly assembled. A truly portable robotic system has many possible applications, such as:

- **nuclear reactor maintenance** (especially for use in different areas of a plant or in two different plants);

- **explosive ordnance disposal (EOD)**, in which a military or police unit could easily and rapidly transport a robot to a new location to defuse or detonate explosives;

- **space operations**, where small, lightweight modules would help meet critical size and weight restrictions.

Each module would have to be carefully designed to be lightweight and durable. The suggested weight limit per module is 35 lbs. Such a weight restriction creates an unusual demand to design light weight actuators and to use special light weight materials (composites or carbon fiber).

PRECISION

The absolute precision of most industrial robots is known to be not better than 0.05 inch, and many are far less accurate. Yet many assembly, welding and light machining operations require a precision of 0.01 inch. Further, fine positioning to 0.001 inch is sometimes necessary.

This level of precision puts an unusually demanding resolution requirement on the actuators and their control system. The control encoders and actuators must be capable of steps of ten seconds of angular rotation. Most actuators fall far short of this, especially if they must provide a high load capacity.

In addition to these precision requirements, the more difficult condition is to maintain precision while the manipulator experiences large load variations. It is common for external loads to degrade the unloaded precision by a factor of ten. The reader can prove this reality to himself by "shaking hands" with a few industrial robots. It is not uncommon to achieve oscillations of 1/4 inch in magnitude. Process disturbances occur from such unit processes as cutting, routing, bending, drilling, force fit assembly, etc.

One possible approach involves intelligent adaptation to system parameter variations. Industrial robots do not exhibit perfectly invariant parameters within the complex control and structural subsystems. The sources of the parametric variations may come from changes in actuator electrical resistance or hydraulic fluid properties, friction in joints, dimensional changes due to temperature fluctuations, and other inconsistent effects. Implicit variations may also be due to imperfect numerical values used in the deterministic model.

The objective is to characterize these parametric variations and to develop a self-organizing adaptive system to compensate with respect to the nominal deterministic model. This "electronically constant" computational scheme could be packaged as software either as hardened design specific ROM or in generic software packages.

Motion command shocks which occur during starting and stopping actions of robotic manipulators induce large oscillations detrimental to precision motion. These shocks represent discontinuous derivatives in the motion program - a concept long recognized in the dynamic programming of precision cam systems.[ref] Researchers at U.T. have been heavily involved with dynamic motion programming of precision high speed cam systems. This work provides a broad analytical scheme which can be applied to 6 DOF spatial motion. Again, software packaging could allow the use of the formulations in a generic or product specific sense.

Precision under loading may be accomplished through an interface of software and hardware component technologies. An "electronically rigid" manipulator could be created by a combination of real time dynamic modelling and distributed joint control.

The dynamic model formulation required is the same as mentioned previously. Using known displacement, velocity, and acceleration information for the motion of the manipulator combined with physical properties of the structure and prime movers and anticipated or measured external loads will allow prediction of nominal deformations. These nominal deformations can then be eliminated through adjustments in control commands in real time. The complexity of the formulation and the required computational speed again imply the necessity of software and computer modules.

There are two pressing problems with small scale motion compensation or "control in the small" with software alone:

- Major actuators required to resist large loads through large motion ranges are simultaneously incapable of meeting high resolution requirements.

- Real time control in large motion ranges can be accomplished adequately if the computational sampling time is modest. Such limited system update rates makes the simultaneous maintenance of high precision operation unlikely.

The best future technology capable of meeting these needs is the dual operation of a manipulator in the large and in the small. Physically, this layering can be accomplished through a high load capacity actuator and a small precision actuator. Computationally, a low speed sampling rate for the full non-linear large motion system and a high speed sampling rate for the linearized small motion system can be achieved.

RELIABILITY

Industrial robots today have established a very high operating availability of approximately 98%. These were marketed only after prolonged testing and redesign. Nonetheless, in other unique applications, this extensive history is not available to ensure high reliability. This property is especially important in remote, hazardous operations like nuclear reactor maintenance and space operations, where a failure would result in huge losses in time and money. Failure is also unacceptable where human life is involved, as in accident missions, military operations or ocean floor activity.

Failure in a robotic system might mean the high cost of total replacement. This maintenance objective would best be met by using robots made up of modules which could be easily replaced. Redundancy in some of the hardware components (sensors, encoders, local microprocessors, etc.) can be helpful. Unfortunately, the need to be lightweight and compact makes reliability more difficult to achieve.

Self-monitoring software, similar to that being used in advanced computers, would be highly desirable. In this regard, self-calibration of the robot system after maintenance or component replacement would be necessary to maintain the match between the control software and the robot hardware.

ECONOMICS

Obviously, economics is an important architectural issue in mechanical design. Compromises in the choices of materials, computer software and hardware, prime movers, sensors, etc. almost always have to be made in order to meet economic realities. Technological developments in these areas will simplify these economic choices.

The modularity approach will allow aggressive upgrading programs to be pursued in almost all major areas. Actuator modules will allow the user to expand the degrees of freedom of a manipulator or replace damaged or worn actuators inexpensively. Computer

hardware can be upgraded and expanded to increase speed and expand capabilities as microprocessor technology improves. Modular software can be inexpensively added to a system to provide dynamic model compensation, metrology for an expanded or adapted manipulator, improved decision making, or integration of improved sensors. An important contribution of the modularity approach is that the system can be expanded or upgraded inexpensively, as opposed to replacing the whole system and starting from scratch.

Advances in materials have allowed manipulators to become stronger and stiffer while decreasing overall size and weight. While some of the newer composite materials are more expensive than conventional alloys, the smaller size and improved capabilities of the manipulator will be worth the cost in many cases.

Many contemporary sensor systems, though rudimentary, are prohibitively expensive. Advanced vision systems, for example, can cost upwards of $200,000. The importance of such systems has fueled a great deal of research and, as with all electronic technologies, advances in sensors will bring better technology at a lower cost. A modular approach, allowing inexpensive software upgrades and hardware replacement, will ease the cost burden of advanced sensor systems.

MODULE TYPES

Specially designed modules with standardized interfaces can be fit together to create a generic, high performance robot. The next generation of robot must be constructed from a large class of near optimum actuator modules which contain their own sub-systems for sensing and (computer) intelligence. Different types of modules can be added to or removed from the robot, depending upon the task at hand.

The modules must be readily scaled (small and large sizes) with standard physical and software interfaces for effortless assembly. Enhanced maintenance due to this modular design is an obvious benefit. This approach is the primary reason that the application of the modular micro-chip is so widespread.

ACTUATOR MODULES

The actuator module concept proposes to combine the joint and prime mover into an interfaceable package. These modules (or building blocks) would be a series of 1, 2, or 3 degree of freedom (DOF) units which could be assembled rapidly by a designer to respond to the requirements of a given application.

Most actuators presently being used in manipulators are off-the-shelf prime movers not specifically designed for precision control of the large coupled motions that occur in robots. This approach does not lead to an optimum balance between the best characteristics of the prime mover and the physical structure of the system. Presently, many actuators are too heavy, have poor response times to commands, generate backlash inaccuracies, have poor resolution, are not stiff under load, and do not contain any local intelligence.

In the design of an actuator, referring to the joint and its associated prime mover, there are four fundamental characteristics which determine the effectiveness with which a manipulator can function. These are strength, stiffness, precision positioning capabilities and component packaging.

The **strength** of an actuator is the measure of the force or torque that it can generate. The load capacity of a manipulator is a direct function of the strength of its prime movers. In a serial chain arrangement, actuators are usually ordered with the strongest component controlling the link closest to ground and subsequent components of decreasing

strength. This configuration results in an efficient match of actuator strength requirements with the strength requirements of the hardware components.

The **stiffness** of an actuator is defined in terms of a functional spring rate which is equal to an applied force or torque at the actuator divided by the deflection that results due to the applied load. The stiffness of actuators in a manipulator chain determines the precision with which the manipulator can perform positioning operations under dynamically varying loads. The required actuator stiffness is directly related to the speed and resolution of the control system. The actuators must be rigid enough to hold a prescribed end-effector (to within a given tolerance) under the maximum force variation that would be expected. If this basic requirement is not met, the actuator could be displaced beyond the acceptable positional tolerance before the system could sense and compensate for the error.

In manipulator systems designed to perform tasks for which external loads are small and precision requirements are minimal, such as spray painting, stiffness is not an important design criteria. On the other hand, the stiffness of a manipulator performing such tasks as force fitting and routing is a critical design objective.

Precision positioning capabilities are determined by many factors, including the sensitivity and resolution of control components, friction in the actuator, backlash in the prime mover, and the mechanical integrity of the structure. All contribute to the precision problem the designer faces and increases the complexity of the solution. The level of positional certainty with which an actuator can function is best quantified on the basis of the "minimum reproducible step size" achievable at the joint parameter.

The control system's contribution to the minimum step size is determined by the resolution of its sensors and the deadband characteristics of its servovalves. Based on these quantities, we can predict the smallest error that can be detected and potentially corrected. In a perfect mechanical system, the control system's precision would represent the precision of the total actuator.

In a real mechanical system, the attainable precision depends not only on the control characteristics but also on the backlash and friction within the device. Backlash occurs in the actuator structure wherever there is clearance in its power train (i.e., between bearings and shafts). Backlash combined with friction and stiction in the actuator creates a mechanical deadband effect that can significantly reduce the precision of operation.

In order to minimize the mechanically related position uncertainties, the use of preloaded bearings (tapered roller bearings or angular contact ball bearings) is recommended. Clearances should be as small as possible. The entire device should be preloaded (if possible) to prevent machine elements from traversing their clearances as the direction of external loading changes. Such preloading must be used judiciously, however, since frictional problems are likely to become more significant.

Component packaging must take into account the physical size and weight of the actuator and the overall utility of the design. The size of a manipulator in relation to its working volume needs to be small in order to increase dexterity and improve obstacle avoidance in the workspace.

Weight must be kept to a minimum to increase payload capabilities and to allow portability for certain applications. The strength to weight ratio of a manipulator's actuators should be as large as possible. Strength requirements of the actuators are determined by the load requirements on the manipulator and the geometry of the manipulator itself. This means that the strength to weight ratio of the system can be improved only by reducing the weight of the actuators.

In addition to all the structural and task related objectives, the designer must also create a "smooth and polished" product attractive in the marketplace.

155

The actuator module concept can go a long way in combining these four fundamental characteristics. For a given joint design, prime movers could be scaled in output characteristics to meet particular task requirements. In addition, the joint itself could be scaled up or down at the discretion of the designer. Stiffness and precision questions could be addressed on a joint by joint basis, allowing a simpler solution to error buildups in serial chains. The very concept of modular actuators requires a compact, clean component easily interfaceable with similar units. Component packaging is thus addressed by the fundamental nature of actuator modules.

SOFTWARE MODULES

As the desired performance of robots is expanded, they will necessarily become more sensor-based and more intelligent. This intelligence will involve an increased level of software. As suggested for actuator modules, the software system will be more rapidly developed and diffused if it is modularized. The system designer will be able to rapidly assemble a total software package from perfected modules that can be easily debugged or replaced with more effective units as they become available. Such modules could be designed to operate at the highest available sampling rates in hardware dedicated to the software module. Since such modules would be widely used, the associated hardware would become much less expensive.

Currently, all manipulators operate open loop, where neither the dynamics nor the external loads are accounted for. The next generation of robotic manipulators will require a high level of precision under loading. Dynamic model formulation in real time will allow compensation to create an electronically precise system.

One of the primary problems limiting progress towards real time operation of intelligent robots is that existing serial processors are poorly suited to treat the fundamentally parallel nature of robotic manipulators. For example, future systems will involve many sensors generating a large information array of all roughly equal significance to the controlling algorithm. There are six distinct computational levels which must be implemented serially in the dynamic model formulation. Within each of these levels, 100 to 800 distinct independent functions can be calculated in parallel. Hence, advances in parallel computer architecture, in association with the modular software, will allow a "smart" module approach.

Candidates for the modular processor approach are sensors, prime movers, joint encoders, end effectors, and vision systems. Each task level would involve sensory data from below interpreted by the module combined with commands from processors higher in the computational hierarchy. The spinal column serves a similar function in the human nervous system.

SENSOR MODULES

Vision, position, proximity, and force information are critical elements of intelligent control, machine intelligence, and precision. Recognition of this fact has generated much in the way of research and development activity. The vast array of sensing systems currently available for implementation on existing manipulators demonstrates the essential modular approach already being pursued in this area.

Vision has long been perceived as an important information feedback technology for intelligent machines. The primary barrier to applications of vision in autonomous operation is that the scene quantification of visual shape data requires high computational times. Further applications of vision systems will depend on increasing computational speeds through parallel processing or other specialized computer architecture. Clearly, the

problems in image analysis will continue to be solved using component technologies in this highly successful example of modularity.

Positional information is required to determine the joint orientations and thus locate a manipulator in space. Precision operation requires high resolution joint position information. Progress in this area is such that angular resolution of 1 part in 1,000,000 is now feasible. Cost does become a factor at these high resolutions. In addition, structural deformation in the manipulator and lack of accurate dynamic modelling can often render such information useless.

Force sensing provides invaluable information which can be utilized within the control loop or as feedback to a man-machine interface. One major advantage of force feedback is that it provides information directly related to system accelerations. This can be useful to supplement or even replace the information obtained by differentiating the position data. Another important usage of force feedback data is in the formulation of the dynamic model.

All methods of measuring resultant forces depend upon the accurate measurement of elastic deformation of a structure of known compliance. Measurements are extracted by a variety of means, including metal film strain gages, potentiometers, piezoelectric materials, and diffused semiconductors in which strain is sensed by a change in resistance. To obtain a complete characterization of forces at the end effector, for instance, requires measurement of six orthogonal force components. It is obvious that a large amount of raw data processing may be required.

Since real time computational speeds are a critical aspect of obtaining intelligent control, the speed at which sensory data is reduced becomes important. Modularity applied to sensor technology could produce a "smart sensor", where preliminary reduction is done at the sensor. This concept would decrease the requirements on the central processor, allowing implementation of advanced control algorithms.

UNIVERSITY OF TEXAS
STRUCTURAL MODULES

The robotics group at U.T. Austin has been involved in the design of structural robotic modules for many years. All of the joint designs stress the modular concept. It is possible then, as with any component designed with modularity in mind, to scale the module to the desired task. Additionally, in applications not requiring 6 DOF, combinations of actuator modules could be assembled as dexterity requires. In all, the joint module approach is seen as a way to quickly implement a manipulator into a given task. The designer is relieved of the burden of an entire system synthesis and can instead concentrate on applications.

ELBOW MODULE

Two separate 1 DOF elbows have been designed. One incorporates a single four bar mechanical amplifier while the other employs two four bar amplifiers in parallel. The latter design (Figure 1a) has been built; two hydraulic cylinders can operate in push-push mode for high positional resolution and a push-pull mode for maximum load capacity. This design goes far in addressing the points of strength, stiffness, and precision and at the same time is compact and modular as required in the component approach.

KNUCKLE MODULE

The 2 DOF knuckle (Figure 1b) again utilizes antagonism. The resulting gains in positional resolution and load capacity are similar to that of the 1 DOF elbow. The knuckle appears isometric in many of its structural properties. Because of intersecting journal axes, it becomes very rigid for its material content. Also, the stiffness of the joint is approximately the same in all directions, which means its assembly into a larger system as a module is not orientation limited. This design does suffer from a limited range of motion about each of its axes; however, this might be quite satisfactory for most applications.

WRIST MODULE

The wrist module (Figure 1c) is another conceptual parallel joint structure. Input from the prime movers is through a triaxial torque tube arrangement. Similar to the shoulder module, the geometry consists of a pair of tetrahedra, but with a moveable base and single link construction. Again, the benefits of parallel structure allow an increase in structural integrity and positioning ability.

SHOULDER MODULE

The 3 DOF shoulder module (Figure 1d) has a parallel structure, with prime movers driving one axis of each link. In essence, the joint consists of a pair of tetrahedra joined together at their edges by three spherical dyads. The parallel structure includes favorable characteristics such as precision positioning capabilities, distribution of loads, and increased stiffness. These characteristics enhance the structural integrity and subsequently reduce the amount of positional error produced. As such, the parallel shoulder could be used as a module in an otherwise serial structure.

CONTROL-IN-THE-SMALL MODULES

Conventional industrial robots have inherent limitations on the accuracy and resolution of end-effector motion, due primarily to the effects of friction, backlash, compliance, and inertia. One approach in dealing with this problem is the addition of a small-motion device, referred to here as a micromanipulator, between the terminal link of the robot and the end-effector. The augmented robotic system thereby retains the gross motion capabilities of the supporting robot while the micromanipulator provides an additional layer of high-bandwidth, high-resolution motions for error compensation, fine manipulation, and delicate force control.

While many researchers have devoted their efforts to the development and implementation of micromanipulating systems, this summary concentrates on the development of a unique, fully-parallel 6 DOF micromanipulator. The rationale for 6 DOF motion is that a typical spatial robot has, in general, corresponding spatial errors. Parallel rather than serial architecture has been chosen for reasons of compactness, rigidity, load capacity, and load distribution.

The particular mechanism that has been selected is a six-legged platform-type device that is specifically designed for small motions. A conceptual hardware design for the micromanipulator is shown in Figure 1e. Direct connection of the upper and lower end of each leg is made through a 3 DOF spherical joint. The desired platform motion is obtained by driving the six independent rotary inputs. Four-bar linkages are used to increase the mechanical advantage of the inputs and to improve the positional resolution of the output, relative to direct actuation of the grounded base joints. Flexural revolute and spherical joints suitable for small displacements have been suggested to avoid the backlash and friction associated with more conventional connections.

As another example of control-in-the-small, the 1 DOF small-control module (Figure 1f) uses a small, secondary prime mover to adjust for minor errors at the joint. This type of module is specifically designed to improve precision.

MINIATURE MANIPULATOR

Another unique concept under study at U.T. is the development of a high precision miniature manipulator. Such a system could be used for inspection, soldering, and electronic circuit assembly. An important new application of robotics could be realized in the field of microsurgery, where a precision manipulator could be operated remotely by a surgeon. An increase in precision of operation by a factor of ten could be achieved by filtering out jitters and oscillations at the input and by changing the scale of motion of the manipulator relative to the surgeon's input.

The conceptual miniature manipulator (Figure 2) consists of three universal (Hooke) joints of 2 DOF each. Since prime movers mounted at the joints would encumber such a small device, control is achieved by using three cables for each joint. Additionally, since the cables are always in tension, backlash is eliminated. Friction problems in the joints can be solved by using jeweled or ceramic bearings. Though by design it is an integral unit, modular concepts in software and control can readily be applied to the miniature manipulator.

In conjunction with the miniature manipulator, U.T. has conceptualized a **miniaturized 6 DOF force sensor** which would provide the extraordinary sensitivity necessary for control in microsurgery and micro-assembly. Figure 3 shows the sensor dome, which would undergo significant controlled deformations under light loading. The inner surface is etched with a micro-circuit in the same manner as used to form foil strain gages. As the circuit is deformed, the resistance measured through 6 distinct circuits would allow determinations of six components of force. Additional circuits may be desirable in more accurate control algorithms.

Due to the large amount of raw data generated, a local processor could be dedicated to create a highly modular package. Calibration and algorithm implementation within the micro-force sensor would create a package suitable for any operation requiring the detection of small forces.

CONCLUSION

Modularity allows each part of a robotic system to be optimally designed, scaled, and interfaced with other modules to produce a generic, versatile robot. The number of manipulator systems that can be derived from a series of such modules is virtually limitless. Once given a broad spectrum of choices, system designers would be able to quickly provide an optimum solution for a particular operation, without being forced to enter a lengthy design and construction phase.

The standardized modules would decrease the cost of a new robotic manipulator and eliminate the possibility of obsolescence - the module can be upgraded when a better model becomes available. The small, standardized modules could be improved less expensively than a whole new robot arm, allowing the robotic industry to make "tech mods" rapidly and take advantage of the most advanced technology. The final result would be a rapidly growing, efficient industry whose impact on manufacturing would rival the impact of the microchip on the field of electronics.

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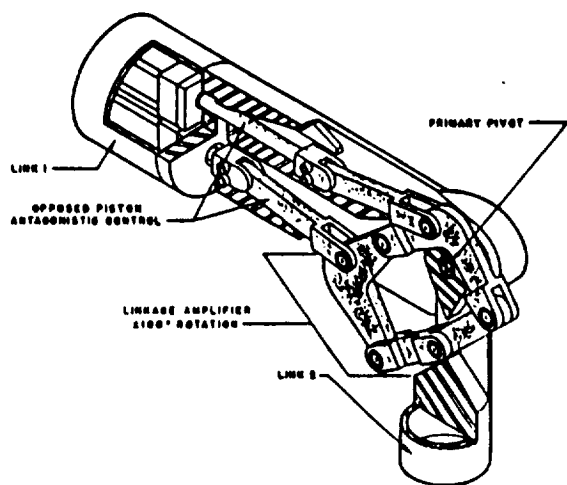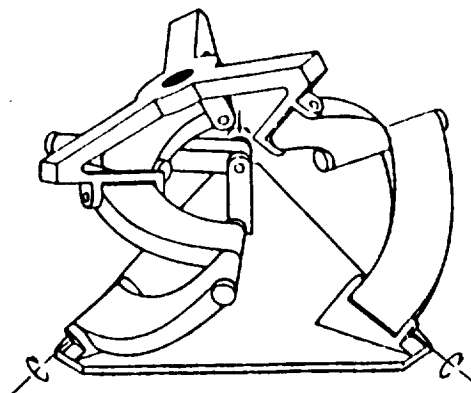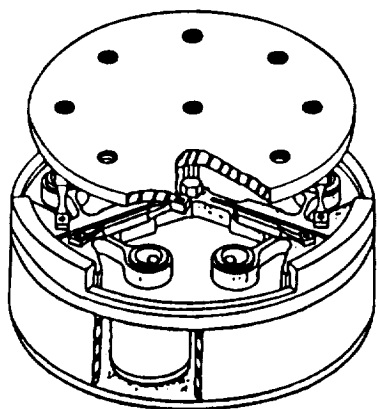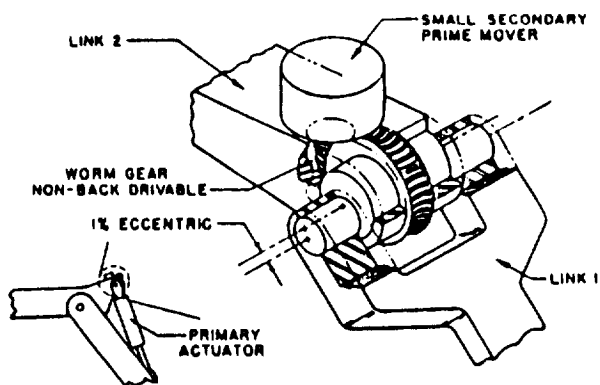
a. 1 DOF Elbow
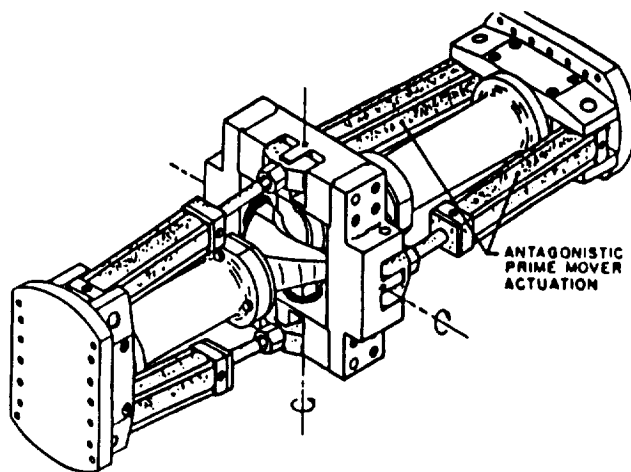
b. 2 DOF Knuckle
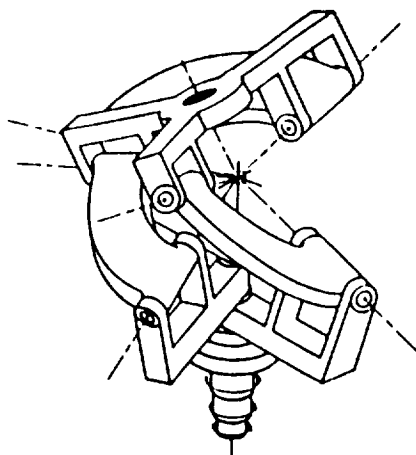
c. 3 DOF Wrist

d. 3 DOF Shoulder

e. 6 DOF Micromanipulator

f. 1 DOF Small-Control Module

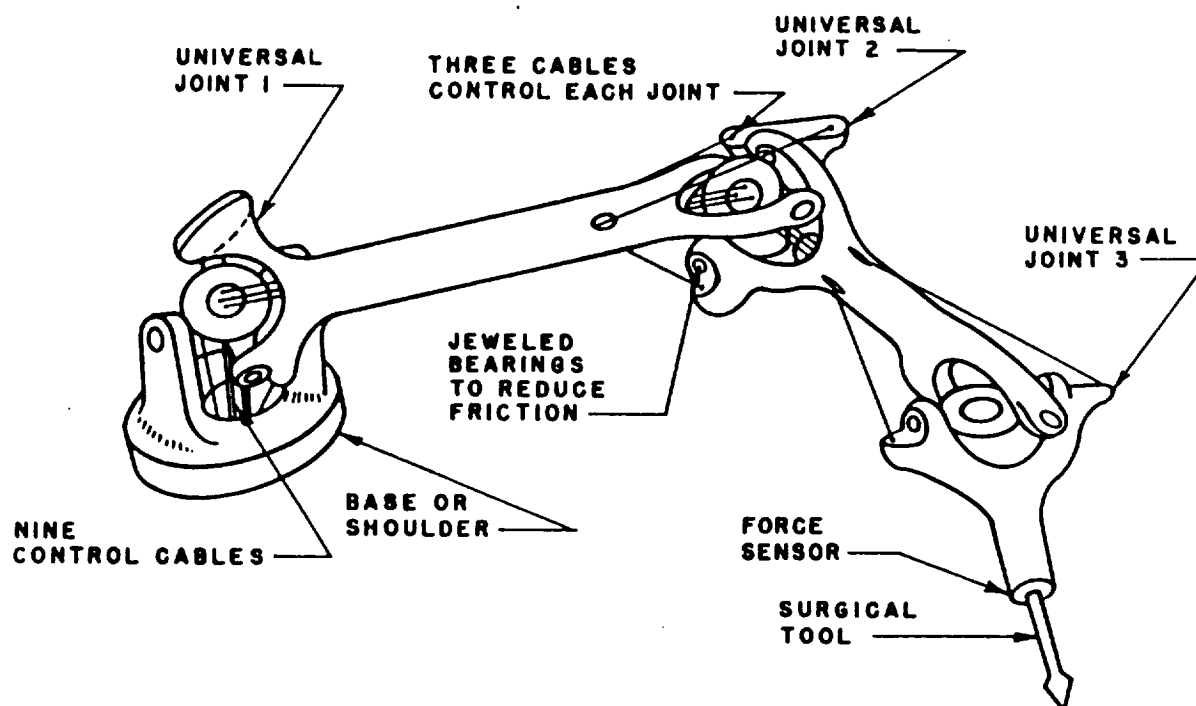Figure 1. University of Texas Structural Modules

UNIVERSAL JOINT I

THREE CABLES CONTROL EACH JOINT

UNIVERSAL JOINT 2

UNIVERSAL JOINT 3

JEWELED BEARINGS TO REDUCE FRICTION

NINE CONTROL CABLES

BASE OR SHOULDER

FORCE SENSOR

SURGICAL TOOL

Figure 2. 3 Inch Miniature Manipulator
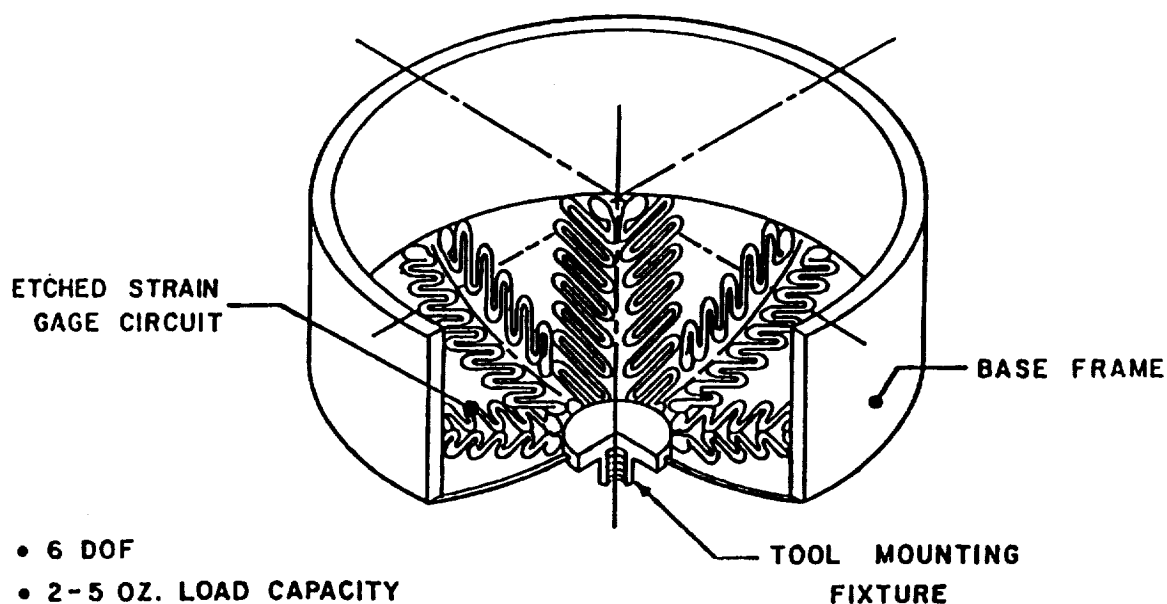

ETCHED STRAIN GAGE CIRCUIT

BASE FRAME

TOOL MOUNTING FIXTURE

- 6 DOF
- 2-5 OZ. LOAD CAPACITY

Figure 3. Micro-Force Sensor